Investigation of Annual Variations in the WCDA GPS Solutions

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BIOGRAPHY

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H. Dragert is a research scientist with the Geological Survey of Canada at the Pacific Gescience Centre in Sidney, British Columbia. He obtained his B.Sc. in mathematics and physics at the University of Toronto in 1968, and his M.Sc. and Ph.D. degrees in geophysics at the University of British Columbia in 1970 and 1973 respectively. He held a NATO post-doctoral fellowship for geomagnetic studies at the Institut für Geophysik, Göttingen, Germany, and returned to teach at the Dept. of Astronomy & Geophysics at UBC in 1974. He joined the Gravity and Geodynamics Division of the Earth Physics Branch in 1976 and moved to the Sidney office at the end of 1978. Over the past 18 years, his principal area of research has been the study of crustal deformation within active seismic areas on the west coast of Canada using repeated precise gravimetric and geodetic surveys.

ABSTRACT

Data from the Western Canada Deformation Array (WCDA), a network of continuous GPS tracking sites located in southwestern British Columbia, have been routinely processed since September 1992. Previous analyses of the WCDA solutions revealed unexplained annual sinusoidal variations in the north component of the three longest-running baselines with amplitudes ranging from 2.1 to 3.4 mm. These variations seem to be correlated with the orientation of the baselines and not the baseline lengths. Precise orbits, which are held fixed in the routine WCDA data reduction, were suspected as the cause in previous reports, though this was not fully proven. Recently, six tests have been carried out in an effort to identify the true cause of these annual variations. From the results of these tests, some factors, such as station-satellite geometry related errors and tropospheric mismodelling, can be discounted. The most interesting result from this study is that a similarity in features is found between the annual variations and an error caused by the uncalibrated GPS satellite antenna offset along the satellite local x-axis. This finding reinforces the suspicion of a systematic orbital error in the precise orbits, al-

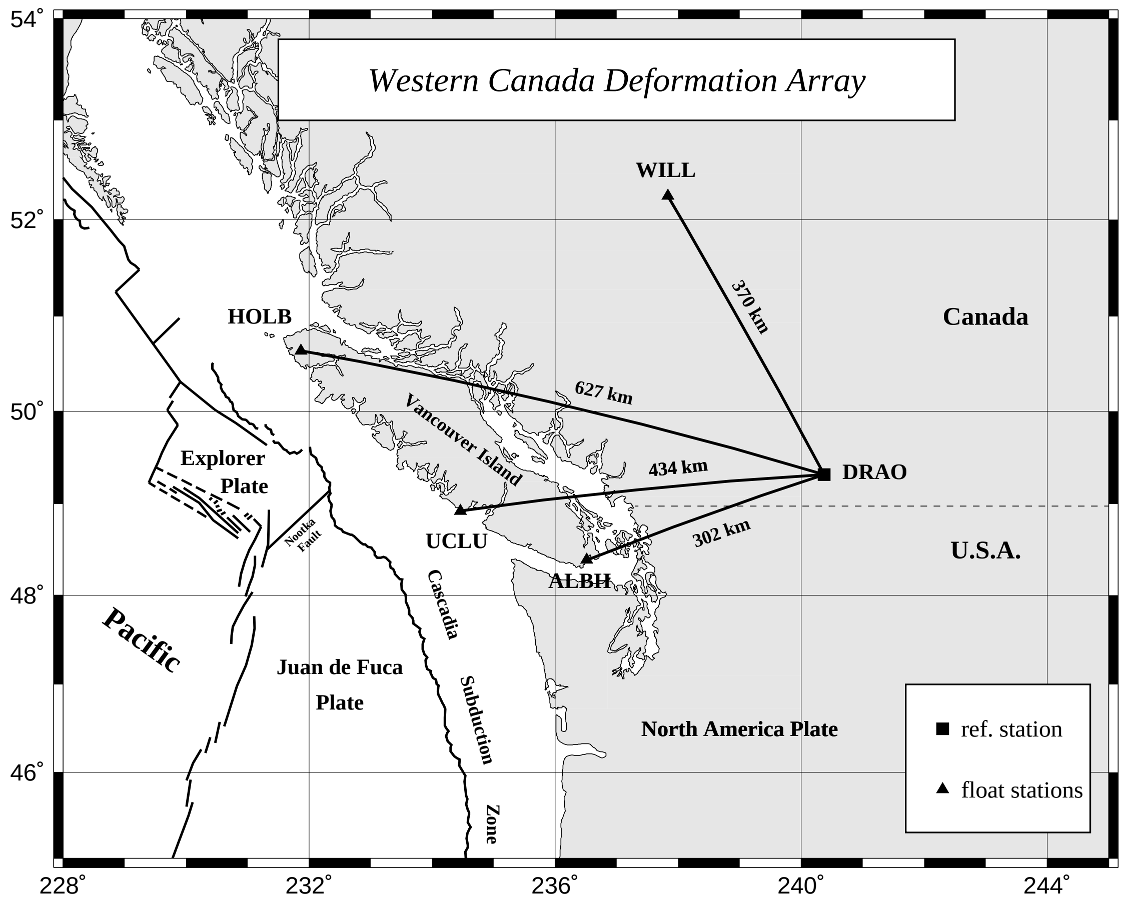

Figure 1: Western Canada Deformation Array.

though common, site-specific, seasonal modulations of the GPS signal cannot be completely ruled out.

1. INTRODUCTION

The Western Canada Deformation Array (WCDA) is a network of continuous GPS trackers located in southwestern British Columbia and operated by the Pacific Geoscience Centre (PGC) of the Geological Survey of Canada, for the purpose of monitoring the crustal deformation across the northern Cascadia subduction zone. The initial set of three permanent stations which were operational by September 1992 included DRAO (Dominion Radio Astrophysical Observatory, Penticton), ALBH (Albert Head, Victoria), and HOLB (Holberg, northern Vancouver Island). Stations added later included WILL (Williams Lake) in October 1993, UCLU (Ucluelet) in May 1994, and NANO (Nanoose Harbour) in May 1995. Through cooperative work with the University of Washington the station NEAH (Neah Bay) was also established on the northwest coast of Washington in July 1995. Figure 1 shows the basic tectonic setting of the region and the configuration of the WCDA prior to May 1995.

The daily analysis of the WCDA data is carried out routinely at PGC using the CGPS22 software developed at NRCan (Natural Resources Canada, formerly Energy, Mines and Resources - EMR) and both NRCan and IGS (International GPS Service for Geodynamics) precise orbits. The estimated parameters are the coordinates of all the non-reference stations, initial double differenced phase ambiguities, and stochastically modelled local tropospheric scale factors. In the estimation, DRAO is used as a reference station and is held fixed to its ITRF (International Terrestrial Reference Frame) coordinates; the NRCan (or IGS) precise orbits in SP3 format (including satellite clocks) are also held fixed; and integer ambiguities are not fixed for final solutions. (For an outline of analysis techniques and a summary of previous results, see Chen

[1994]; Chen et al. [1995]; and Dragert et al. [1995]). To briefly summarize the earlier results, a precision of several millimeters was achieved for both horizontal and vertical components for baseline lengths ranging from 302 to 627 km. Error analysis on the results revealed the presence of some systematic errors including remarkable multipath effects present in the east component of baseline ALBH-DRAO, elevation cut-off angle dependent offsets due to antenna phase centre variations, and annual sinusoidal variations present in the north component of most if not all of the WCDA baselines. The last of these systematic errors has an uncertain cause and is the focus of the present investigation.

In order to help identify the cause of the annual variations, several tests were carried out on older data sets. These tests dealt with the tropospheric modelling, the polynomial representations of the precise orbits, the tidal corrections, the station-satellite geometry related factors, and the satellite antenna offsets. Although these tests did not identify an unambiguous cause, they were successful in defining important features of this error and in narrowing the scope for future investigations. This paper discusses the various aspects of these tests: Section 2 gives a brief review of the features of the error and describes the conducted tests; Section 3 outlines the results of the tests; Section 4 discusses some of these results in greater detail; and Section 5 summarizes the current study.

2. FEATURES OF THE ERROR AND DESCRIPTIONS OF THE TESTS

From previous studies, the features of the annual variations present in the north component of the WCDA solutions can be summarized as follows:

1. The amplitudes vary from 2.1 to 3.4 mm. There is a suggestion that these amplitudes are correlated with baseline orientation and not baseline length.
2. The variations on different baselines seem to have a similar phase pattern and the same annual period.
3. The variations are insensitive to changes in satellite elevation cut-off angle and antennas (at both the reference and non-reference stations).
4. Variations with these characteristics do not appear in the east or upward baseline components.

Feature 1, the variation of amplitudes, tends to rule out local deformations such as the tilting of the antenna pillar at the reference site DRAO as the source of this error. Feature 2 implies that local, physical phenomena at non-reference stations are unlikely to be the cause of these variations. However, this cannot be totally ruled out since there does exist a commonality in the mounting of the antennas at all sites (i.e. forced-centre brass mounting plates embedded atop concrete pillars). Feature 3 argues against seasonal multipathing variations being the cause while feature 4 suggests that tropospheric mismodelling and tidal mismodelling are unlikely causes since these would affect the upward and the east components more than the north components. This process of (uncertain) elimination leaves precise orbits as the likeliest candidate for the observed annual variations [Chen, 1994; Chen et al., 1995].

Still, to maintain a wide of search for the cause of this error, we chose to investigate not just the precise orbits but also other related aspects, including not only the "less likely" causes outlined above but also the possible existence of some small as yet undetected software bugs which somehow only manifest themselves over longer periods of solutions. In summary, six main tests have been carried out, as described below.

Test 1 is a test of the polynomial representation of the precise orbits. The standard precise orbits are tabulated at 15-minute intervals, and normally in CGPS22, the precise orbits are represented by Chebyshev polynomials of order 15 for each satellite pass (roughly 6 hours). We chose to use two arbitrarily chosen days of JPL-generated precise orbits to do the test, since we managed to obtain both 15-minute and 5-minute tabulated precise orbits. By comparing the polynomial interpolation of the 15-minute sampled orbits with the 5-minute sampled orbits, the accuracy of the polynomial representation could be evaluated.

Test 2 involved toggling on/off some of the measurement correction models, specifically the solid earth tide and the ocean loading plus pole tide. Since tidal effects are predominantly in the vertical component, this test is mainly for identifying software bugs related to these corrections, although it is also interesting to see the impact of these corrections on the solutions.

Test 3 involves carrying out daily moving-window solutions using 12-hour data segments with start-times moved forward 4 minutes each day, consistent with the daily advance of the satellite geometry. The purpose of the test is to identify any station-satellite geometry related errors such as multipath and phase-centre variations.

Test 4 estimated the x, y, z biases in the satellite local coordinate system. It was designed to test if there are any systematic errors with regard to the satellite orbits and the phase center calibration of the satellite transmitting antennas (offset of phase center from center of mass).

Test 5 was a test of the tropospheric propagation delay modelling in CGPS22, which uses Hopfield's model for zenith tropospheric delay, Black's mapping function, and a colored noise stochastic process for the local tropospheric scale factors. Obviously there are three areas to test: the model for the zenith tropospheric delay, the mapping function, and the stochastic model. Firstly, Saastamoinen's model was used to replace Hopfield's model; secondly, the more up-to-date Herring and Niell mapping functions recommended by Mendes and Langley [1994] were adopted to replace Black's mapping function; and lastly, a random walk noise process and different parameterization schemes for the tropospheric delay were tested. The parameterization schemes include: estimating the residual combined wet and dry (non-hydrostatic and hydrostatic) zenith tropospheric delay (default in the routine WCDA data reduction), estimating the total combined wet and dry delay without any *a priori* calibration, and estimating a stochastic wet delay and a constant dry delay with *a priori* calibration.

Test 6 involved replacing the NRCan precise orbits with the IGS precise orbits. The IGS precise orbits are a combination of the precise orbits generated by several IGS analysis centers. They are formed by weighted averaging and removing small reference frame errors from the individual precise orbits with respect to a common reference frame. The IGS precise orbits are claimed to be comparable to, or better than, the best individual orbits [Beutler et al., 1995]. Consequently, this test can identify possible biases in the NRCan orbits. However, since the IGS orbits and NRCan orbits are both inherently correlated with each other due to similar fundamental mathematical formulations for orbit modelling, existence of errors common to both orbits are possible and would not be detected in this test.

3. RESULTS OF THE TESTS

The tests described in the last section were carried out using all of the WCDA data collected in 1994. The results are summarized briefly as follows:

Test 1: The comparison between the interpolated orbits using Chebyshev polynomials fit from the standard 15-minute tabulated precise orbits and the 5-minute tabulated precise orbits reveals that with a polynomial order equal to or higher than 15, the root mean square (rms) errors for all satellites are well below 1 cm. Reducing the polynomial order below 14, results in larger errors (> 1 dm) for some satellites. We conclude that the polynomial order 15 used for routine WCDA data analyses is more than adequate and this interpolation of orbits procedure does not generate a seasonal error.

Test 2: A comparison was made among the routinely obtained solutions, the solutions without ocean loading and pole tide corrections, and the solutions without any tidal (including solid earth tides) corrections. The annual variations in the north components are found to be almost completely unaffected by the addition or ommission of these corrections. This is not surprising since all tidal effects are confined to mostly the vertical component. However, it is somewhat surprising that the solid earth tide correction does not improve the precision of the vertical component significantly but appears to improve the precision of the horizontal components by 0.1 to 0.3 mm for almost all baselines. On the other hand, the ocean loading correction improves estimates of the vertical components but degrades slightly the estimates of the horizontal components (see Chen [1996] for more details).

Test 3: The 12-hour moving-window solutions show somewhat larger scatters compared to the routinely obtained 24-hour daily solutions, and still exhibit the same annual variations. This indicates that factors related to the station-satellite geometry probably do not play a significant role in the annual variations. This does not rule out multipathing and/or antenna phase center variations as potential causes since these factors might be modulated seasonally at individual sites.

Test 4: This test produced unexpected results. An examination of mean residuals for the satellite antenna offsets revealed zero offsets in the y and z axes, but an offset of 0.279 m in the x-axis. Further investigation revealed the software error which caused this problem. After correction of this error, all the estimated residual x, y, z satellite antenna offsets became zero. Table 1 lists the precisions of the original solutions and the precisions of the solutions recomputed with the corrected satellite antenna offset. These precisions are calculated as the root mean square (rms) scatters about a best fitting line through the daily solutions. The precisions for the east (E) component of the ALBH-DRAO baseline and the upward (U) component of the WILL-DRAO baseline are not listed since they are contaminated by large errors due to multipath effects and antenna phase center variations [Chen et al., 1995]. The most marked improvement occurs for the north component of the baselines HOLB-DRAO and WILL-DRAO (0.5 and 0.6 mm respectively), which are "coincidently" also the two most severely affected by the annual variations. Slightly suppressed as they are in the amplitudes, the annual variations remain in the recomputed solutions with the same features except for the somewhat smaller amplitudes. There is a striking similarity between the error caused by this x-axis satellite antenna offset and the annual variations in the north component of WCDA baselines, prompting additional analyses of these results which are discussed in the next section. It should also be noted that all other tests used the corrected version of the software.

Test 5: This test took the most intensive efforts. Four sub-tests were carried out, and the results were then compared (in all three baseline components) to those using the original tropospheric estimation strategy (Hopfield's model, Black's mapping function, and colored noise process with 10 hours correlation time and 5% steady state sigma). In the first sub-test, Herring's mapping function was used to replace Black's

Table 1: Precisions in mm in north, east, and upward components for the original solutions and the recomputed solutions with correct calibration of the x-axis satellite antenna offset.

Baseline	*Original*			*Recomputed*		
	N	E	U	N	E	U
ALBH-DRAO	2.1	-	7.3	2.2	-	7.4
UCLU-DRAO	2.2	2.8	6.4	2.1	2.8	6.6
HOLB-DRAO	3.5	3.7	7.3	3.0	3.5	7.6
WILL-DRAO	3.5	3.2	-	2.9	3.2	-

Table 2: Precisions in mm in north, east, and upward components for solutions using the IGS precise orbits

Baseline	*IGS*		
	N	E	U
ALBH-DRAO	2.1	-	7.4
UCLU-DRAO	2.1	2.8	6.5
HOLB-DRAO	2.8	3.5	8.0
WILL-DRAO	2.8	3.1	-

mapping function. The results indicated that both mapping functions gave almost identical solutions with few differences of 0.1 mm. The second sub-test estimated the total combined tropospheric wet and dry delays without any *a priori* calibration. This method is described and recommended by Tralli and Lichten [1990]. However, the results of this sub-test turned out to be comparable (within $\pm$0.1 mm) to those using the original estimation strategy. The third sub-test used Saastamoinen's tropospheric model along with Niell's mapping function and a random walk process for the residual combined wet and dry delay. Again, the results were not significantly different from the results with the original estimation strategy. The last subtest estimated the wet delay and dry delay separately. The residual wet delay was estimated as a stochastic process, and the residual dry delay as a constant variable. The results of this last test showed comparable or slightly worse precisions. The conclusions that can be drawn from these tests are that the original tropospheric estimation strategy is totally satisfactory for the routine reduction of WCDA data, and more important, the annual variation in the north component persists no matter what tropospheric estimation strat-

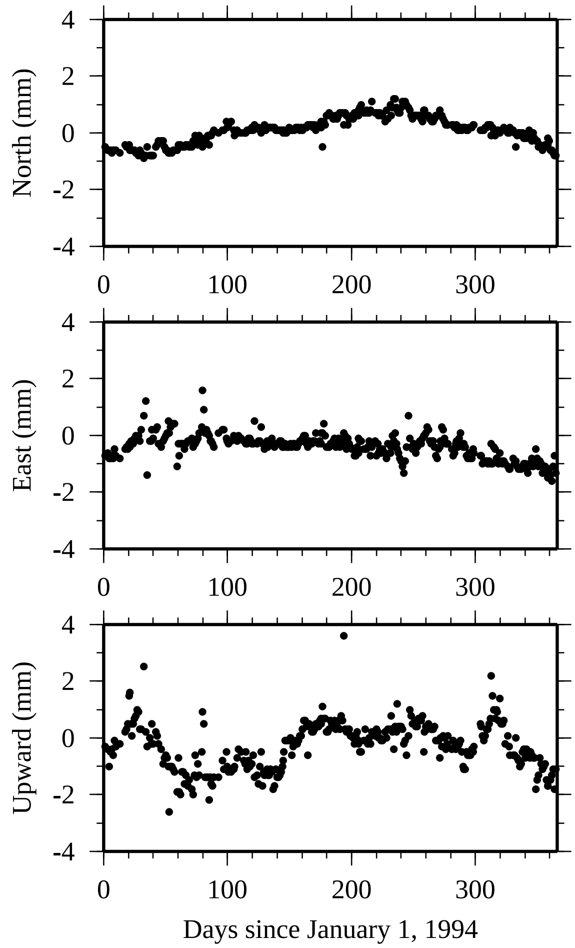

Figure 2: The errors induced by the uncalibrated x-axis satellite antenna offset for baseline ALBH-DRAO

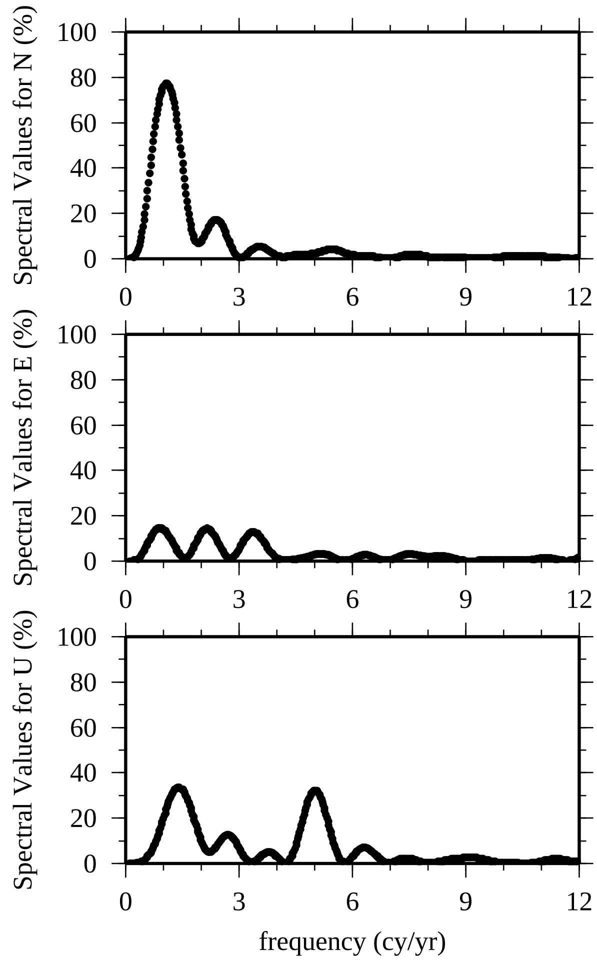

Figure 3: The LSSA spectra of the errors in Figure 2.

egy is used.

Test 6: The precisions obtained using the IGS precise orbits are summarized in Table 2. Compared with the precisions of the recomputed solutions using the NRCan precise orbits in Table 1, it is evident that the solutions with IGS orbits generally show slightly better precisions. This verifies the better quality of the IGS orbits. More important to this study, the annual variations in the north component remain the same with the IGS precise orbits. Therefore, the NRCan precise orbits are in good agreement with the IGS precise orbits and cannot be singled out as the cause of this annual variation. However, as stressed in the last section, errors common to both IGS and NRCan precise orbits may exist and cannot be detected by this test. Thus the precise orbits as a whole, be they from IGS or NRCan, should not be dismissed from further investigations.

4. ANALYSIS

Least Squares Spectral Analysis (LSSA) [Wells et al., 1985] was carried out on the results from test 4. First the WCDA solutions were recomputed using the correction for the x-axis satellite antenna offset. Then the time series formed by differencing the recomputed solutions and the original solutions (without the correction for the x-axis satellite antenna offset) was obtained. This time series should represent the effect caused by the error in the satellite antenna offset. Figures 2 and 3 show the differenced time series in north, east, and upward components for baseline ALBH-DRAO and their corresponding LSSA spectra. Figures 4 and 5 show the same quantities for baseline WILL-DRAO. It is interesting to see that the north component is affected most strongly in a systematic way with a dominant annual frequency. This statement holds true for the other two baselines, although the magnitude of this error differs from baseline to

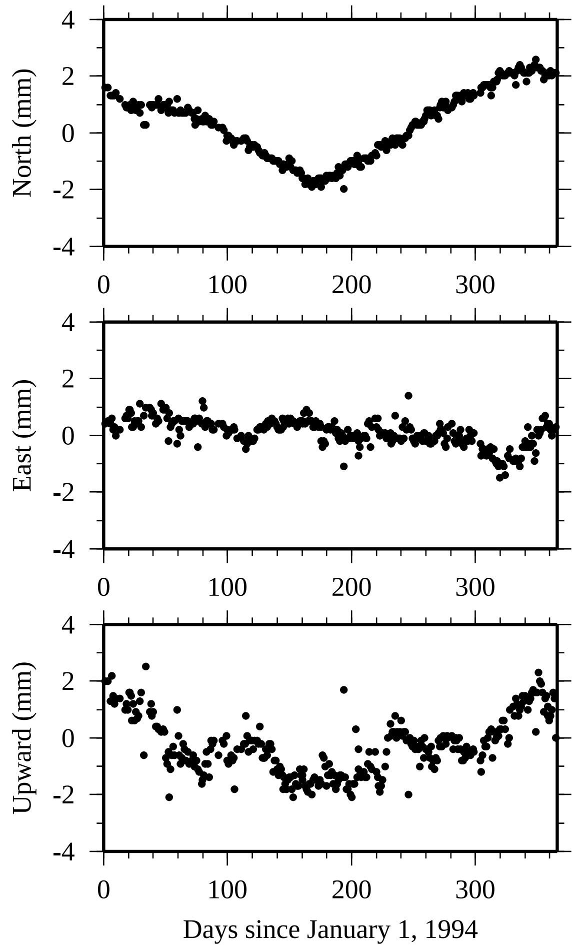

Figure 4: The errors induced by the uncalibrated x-axis satellite antenna offset for baseline WILL-DRAO.

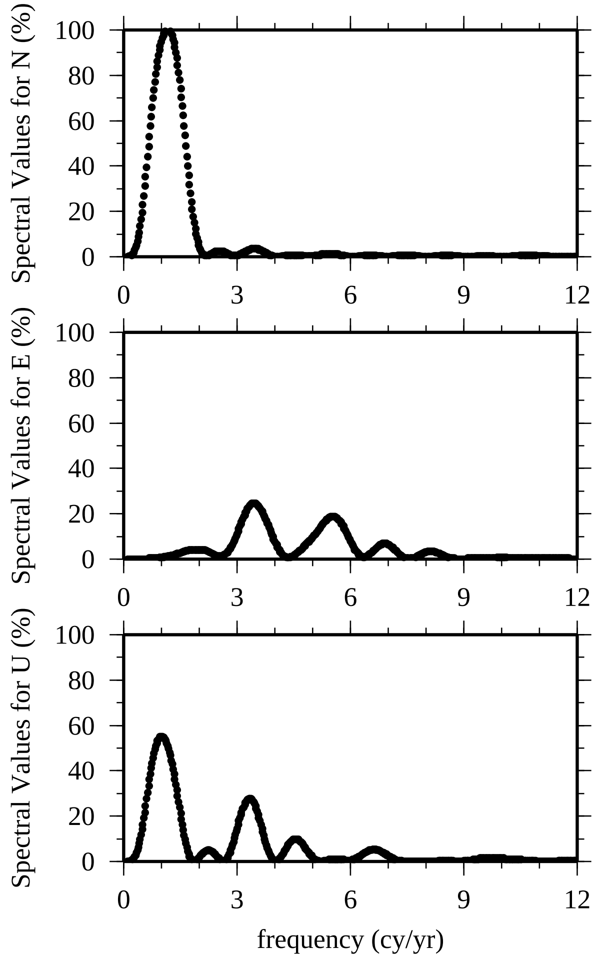

Figure 5: The LSSA spectra of the errors in Figure 4.

baseline.

Figure 6 illustrates the north component of this error for all the WCDA baselines. Note that the baselines in Figure 6 are arranged in an order according to the orientation of the baselines (see Figure 1). Table 3 lists the amplitudes and phases of the dominant annual periodic constituents for the quantities shown in Figure 6, along with the corresponding formal errors. Evidently from Figure 6 and Table 3, the amplitude of this error is strongly dependent on the orientation of the baselines and not baseline lengths, as one might typically expect for orbital errors! The phase of the error also appears to be increasing systematically as a function of baseline orientation.

To allow direct comparison to the error residuals of Figure 6, the daily variations in the north component apparent from the recomputed WCDA solutions have been plotted in the same order for the four baselines (see Figure 7). Table 4 lists the amplitudes and phases of the dominant annual periodic constituents for the quantities shown in Figure 7. (It should be noted that the estimates in Table 4 are subject to larger errors than those in Table 3.) A comparison of the two tables and two figures shows a striking similarity between the two data sets, although Table 4 exhibits no clear trends in the phases of the annual variations. For example, in both Figures 6 and 7, all the baselines have a dominant annual period (even for ALBH-DRAO in Figure 7, although its LSSA spectral value is only about 6%), and the phases for WILL-DRAO and HOLB-DRAO are very close. Moreover, the two sets of amplitudes in Tables 3 and 4 are proportionally consistent even though the formal errors for the amplitudes in Table 4 are larger. For instance, taking the amplitude of ALBH-DRAO as 1 in both tables, the relative amplitudes in Table 3 would be 1.0, 1.6, 2.3, 2.7, and 1.0, 1.7, 3.0, 2.8 in Table 4. The large differences in the

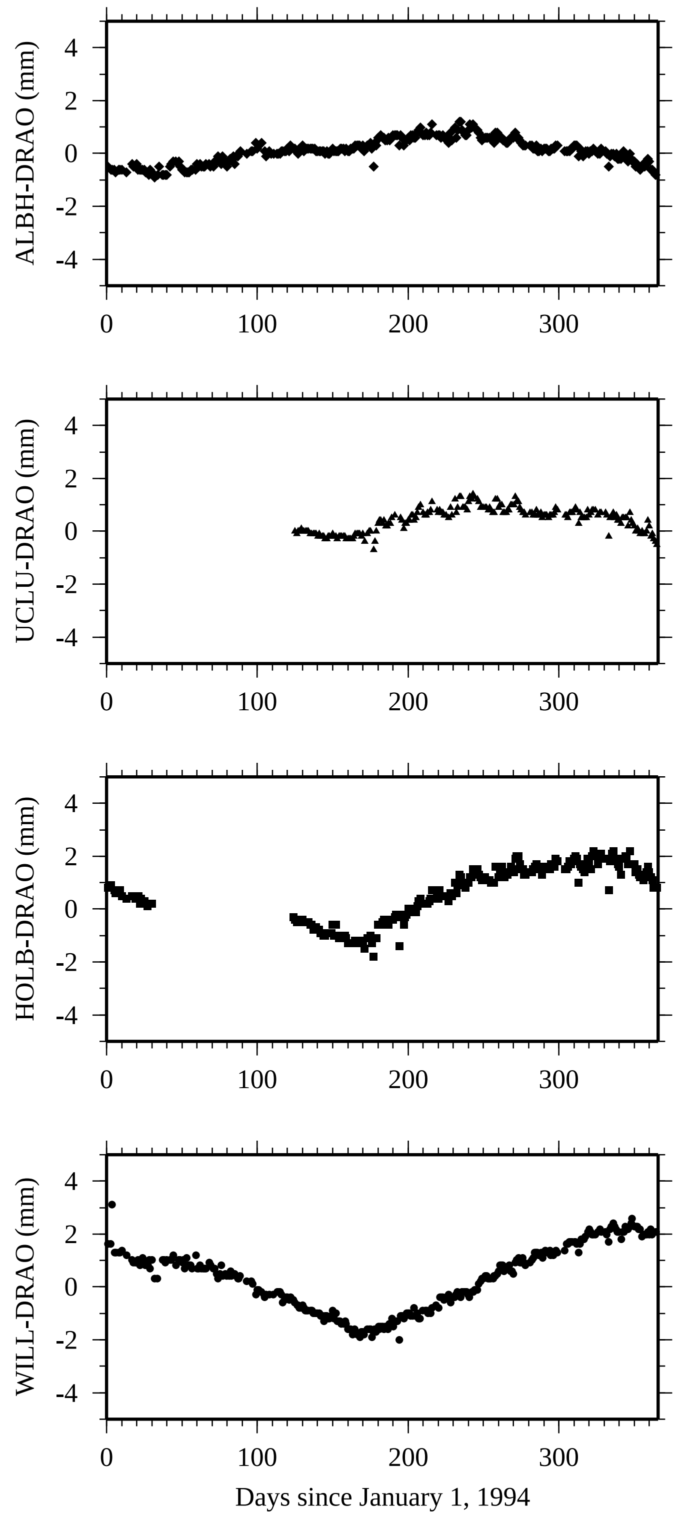

Figure 6: North component of the error time series caused by the incorrect x-axis satellite antenna offset in the WCDA solutions.

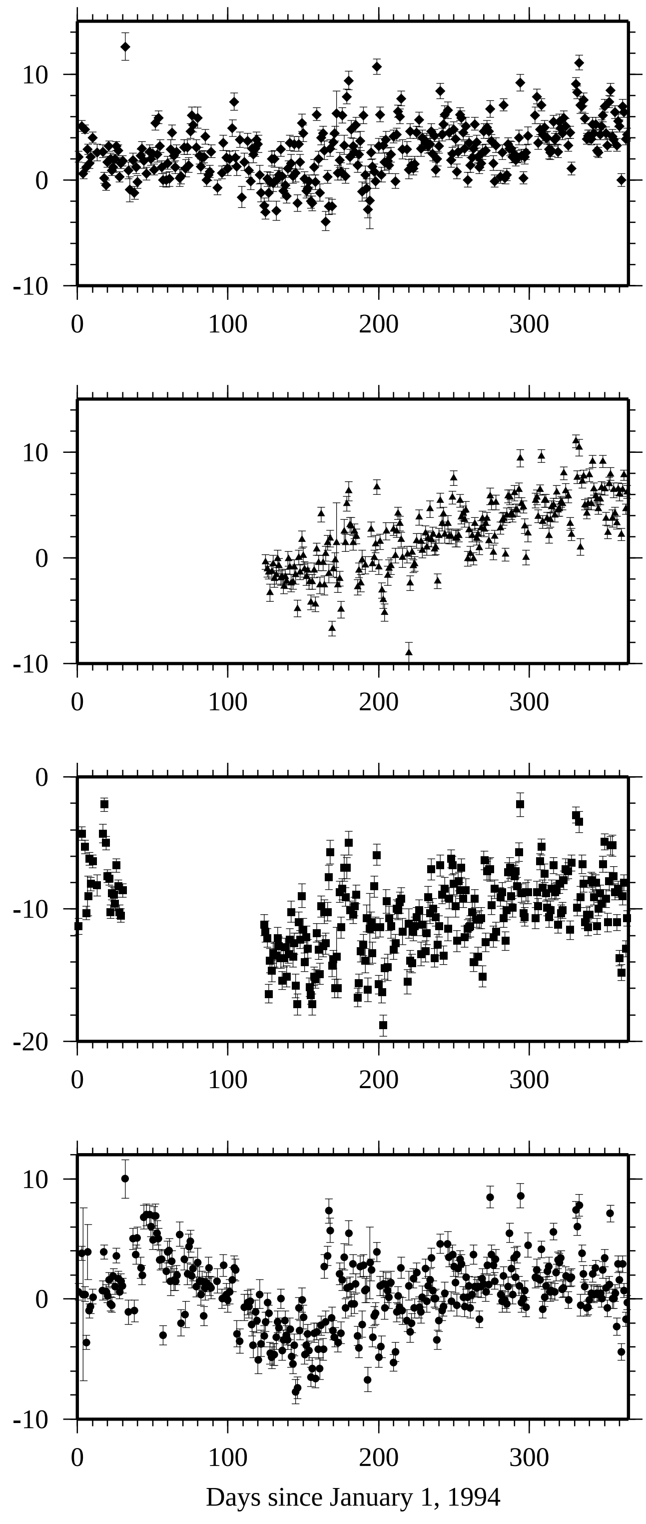

Figure 7: North component of the WCDA baselines after the correct calibration of the x-axis satellite antenna offset (plots are in the same order and with the same units as in Figure 6).

Table 3: The estimated amplitudes and phases of the annual constituent present in the north component of the differenced time series for the WCDA baselines.

Baseline	Amplitude (mm)	Phase (deg)
ALBH-DRAO	0.59 ± 0.03	220.45 ± 2.17
UCLU-DRAO	0.96 ± 0.09	282.92 ± 5.99
HOLB-DRAO	1.38 ± 0.07	306.05 ± 3.37
WILL-DRAO	1.58 ± 0.02	353.17 ± 1.93

Table 4: The estimated amplitudes and phases of the annual constituent present in the north component of the recomputed WCDA solutions.

Baseline	Amplitude (mm)	Phase (deg)
ALBH-DRAO	0.89 ± 0.22	329.46 ± 15.07
UCLU-DRAO	1.50 ± 0.86	332.91 ± 18.09
HOLB-DRAO	2.63 ± 0.29	319.72 ± 18.26
WILL-DRAO	2.54 ± 0.28	319.18 ± 16.67

phases for ALBH-DRAO and UCLU-DRAO are possibly due to the comparatively smaller amplitudes for the two baselines and contamination by other errors.

It should be pointed out here that the above comparison does not prove that the annual variations in the north component of WCDA baselines are directly related to satellite antenna offsets. Rather, it showes that a systematic orbital error, like the error in the x-axis satellite antenna offset described above, can result in an annual signal similar to the observed variations. Consequently, it is reasonable to conclude that an unmodelled or mismodelled physical phenomenon in the precise orbits remains the primary suspect for the cause of the annual variations in the WCDA solutions. The exact cause awaits further data and further analyses.

5. SUMMARY

Six tests have been carried out in a search for the cause of the annual variations present in the north component of the WCDA solutions producing some notable results. The errors related to the station-satellite geometry and the mismodelling of the tropospheric propagation delay are found to be unlikely causes of these variations. The quality of the polynomial represention of the precise orbits in the CGPS22 software and the quality of the IGS precise orbits are verified, although the improvement with IGS orbits over the NRCan orbits is marginal. Tests involving tidal effects confirm that no errors are introduced through ocean-loading and pole-tide corrections nor through solid earth-tide corrections. Most interestingly, it was found that an error in the calibration of the phase center offset of the satellite antennas along the satellite local x-axis led to error residuals with features similar to the observed annual variations in the north components. Consequently, the suspicion that systematic orbital errors are the cause of the annual variations is reinforced, although the identification of the exact cause awaits the involvement of IGS analysis centres and further studies.

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